An Improved Prediction Model of Vortex Shedding Noise from Blades of Fans

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The main source of the noise of an axial flow fan is the fluctuating pressure field on blade surfaces caused by the shedding of vortices at the trailing edge of blades. An analytical model to predict the vortex shedding noise generated at the trailing edge of blades of axial flow fans was proposed by Lee in 1993. In this model, for mathematical convenience, an idealized vortex street is considered. However, the agreement between the analytical results and the experimental data needs to be improved because of the simplification about the Karman vortex street in the wake of blade. In the present study, a modified model is proposed based on the prediction model by Lee. The boundary layer theory is used to analyze and calculate the boundary layer development on both the pressure and the suction sides of blades. Considering the effect of boundary layer separation on the location of noise source, the predicted overall sound pressure level compares favorably with the experimental data of an axial fan. In the calculation of A-weighted sound pressure level (L_A), considering the effect of static pressure on radiate energy, the predicted broadband noise with the modified model compares favorably with the experimental data of a multiblade centrifugal fan.

Keywords: vortex shedding noise, broadband noise, boundary layer separation, fan

Introduction

Considering the environments of working and life, the problem of noise generated by fans has been obtained great concern over the recent years. The aerodynamic noise of fans is very dominant in fan noise, rather than the mechanical noise caused by vibration and the electromagnetic noise caused by motor [1]. Lighthill [2] showed that the vortex shedding noise generated from the wake of blades of fans is the main source of noise.

Several prediction models of noise based on Karman vortex street have been widely utilized for the prediction of noise from axial fans or centrifugal fans. Sharland [3] proposed that the broadband noise of an axial flow fan can be described by three mechanisms, surface pressure field arising from the turbulent boundary layer, influence of the vortex shedding from the surface of a rigid body, and the incoming flow with initially turbulent flow. Lee [4] proposed an analytical model for predicting the vortex shedding noise generated from the wake of axial flow fan blades. Wang [5] developed a noise model and optimized the algorithm of boundary layer development.

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Wang [6] presented an analytical model for predicting the noise of plenum fan based on the structure characteristics of centrifugal impeller. Khelladi [7] showed that in a far field a monopolar source is equivalent to a dipolar source induced by a uniform distribution of the load on the entire moving surface. Sasaki [8] proposed a prediction theory for the broadband noise generated from a multiblade fan based on the characteristics of the Karman vortex street. Capece [9] investigated the unsteady flow phenomena resulting in the differences in the instantaneous rotor blade wake data. In these researches, it is well agreed that the noise generated by vortex shedding is the primary source of noise for small fans.

In the present work, an improved predicting equation of broadband noise generated by fans is proposed. With this improved equation, the predicted broadband noise compares favorably with the experimental data of a multiblade fan in the literature [8].

Model and Method

Lee developed an analytical model for predicting the vortex shedding noise generated from the wake of axial flow fan blades [4].

According to the stability analysis of the Karman vortex street, the distance between vortex rows can be estimated by [4],

$$b = 0.6\delta_{ss} + 0.6\delta_{sp} + d \tag{1}$$

where b is the distance between vortex rows, d is the trailing edge thickness, δ_{ss} and δ_{sp} are the boundary layer thickness on suction surface and pressure surface, respectively.

$$s = \frac{b}{a} = 0.281 \tag{2}$$

where s is a constant, and a is the distance between vortices.

The vortex strength can be written as [4],

$$K = \frac{V\left[\pi sa - \sqrt{(\pi sa)^2 - 2\pi a(\theta_{ss} + \theta_{sp})(2\pi s\tanh(\pi s) - 1)}\right]}{2\pi s\tanh(\pi s) - 1} \tag{3}$$

where K is the strength of each individual vortex, V represents the main flow velocity, and θ_{ss} and θ_{sp} are the momentum thickness of boundary layers on suction surface and pressure surface, respectively [4].

The whole vortex street has an advance velocity, V_i = ($K/2a$) tanh (πs), then the vortex shedding frequency is given by [4],

$$f = (V_r - V_i)/a \tag{4}$$

The Strouhal number based on the trailing edge thickness is written as [4],

$$\mathrm{St} = fd/V_r \tag{5}$$

The pressure distribution can be written as [4],

$$p(x,t) = -\frac{\rho KV}{\pi}\sum_{n=1}^{\infty}(-1)^n\left\{\frac{\alpha_n}{\xi_n - x}\sqrt{\frac{(c/2)+x}{(c/2)-x}}\sin(\omega t) + \frac{\omega c}{2v}\left[\alpha_n\cos^{-1}\left(\frac{-x}{c/2}\right) - 2\tan^{-1}\left(\frac{1}{\alpha_n}\sqrt{\frac{(c/2)+x}{(c/2)-x}}\right)\cos(\omega t)\right]\right\} \tag{6}$$

where ρ is the density of air, c is the chord length, and ω is the angular velocity,

$$\omega = 2\pi(V_r - V_i)/a \tag{7}$$

$$\alpha_n = \sqrt{(\xi_n + c/2)/(\xi_n - c/2)} \tag{8}$$

In Eq. (6), ξ_n is the distance from the centre of vortices to the origin which is located at the centre of blade.

In Lee's study, for mathematical convenience, an idealized vortex street (see Fig. 1) has been considered, where c is the chord length. In Fig. 1, the origin o is set at the centre of airfoil. The noise source is considered to be at the trailing edge of blade since it is assumed that the vortex shedding occurs at the trailing edge.

However, since the boundary layer flow at the suction side of the blade is under adverse pressure gradient at an attack angle, it is easy to be separated from the blade surface (see Fig. 2). When the boundary layer is separated, vortices would be generated immediately from the separation point. At high Reynolds number, vortex shedding could be produced upstream at the separation point rather than at the trailing edge of blades.

Figure 3 shows the flow around an airfoil which is taken from a cascade and is studied at the attack angle β of 17.5 degree [10].

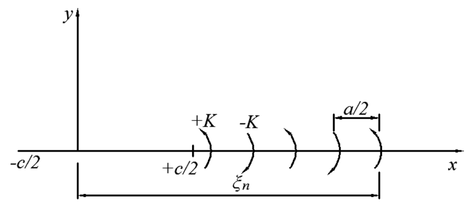

Fig. 1 Idealized model of vortex street

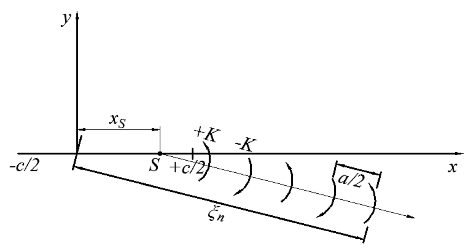

Fig. 2 Modified model of vortex street

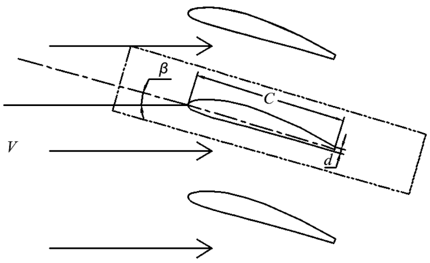

Fig. 3 Schematic diagram for airfoil

As discussed above, considering the separation of boundary layer, the location of noise source may be moved from trailing edge to the separation point. Taking into account of this phenomenon, an improved calculation equation of noise is proposed as follow,

$$\xi_n = x_S + na/2 \tag{9}$$

In Eq. (9), the first term x_s stands for the distance from the origin o (the center of blade) to the separation point S, and the second term represents the distance between a shedding vortex and the separation point S.

The sound power e radiated from the incoming flow field can be expressed as [4],

$$e = \frac{\rho}{24\pi a_o^3} \int_{span} \frac{(KVV_i)^2}{cb_x b_z} \times \left\{ \left[\sum_{n=1}^{\infty} (-1)^n (\alpha_n - 1) \right]^2 + \left[\sum_{n=1}^{\infty} (-1)^n \frac{\omega c}{2V} \left(\alpha_n - \frac{1}{\alpha_n + 1} \right) \right]^2 \right\} dz \tag{10}$$

where a_0 is the speed of sound, the constants b_x and b_y are 0.19 and 0.71, respectively [11], and the first 50 terms taken from the series can meet the actual computing requirements [6].

In reference [8], Sasaki et al. did experiment for a multiblade centrifugal fan and compared the experimental result with the prediction with Lee's classic model [4]. It is found that the agreement between the theory and the experiment is very poor. Therefore, an improvement is needed on Lee's theory for prediction of broadband noise. In the following, considering the effect of the static pressure in vortex flow domain, the equation for calculating the frequency of broadband noise generated by vortex shedding is proposed. The frequency of vortex shedding can be written as [8],

$$f = \mathrm{St} \times V_r d^{-1} \tag{11}$$

where St expresses the Strouhal number and the V_r is the relative velocity at impeller outlet.

The total pressure represents the total mechanical energy of fluid. The level of total pressure at impeller outlet can be used to characterize the noise level. The total pressure consists of the static pressure and the dynamic pressure,

$$P_t = P_{st} + \frac{\rho}{2} V_a^2 \tag{12}$$

where P_t is the total pressure, P_{st} is the static pressure, and V_a is the absolute velocity at impeller outlet.

In the flow model [8], the flow has been divided into two domains. One is a domain with the vortex flow at the bellmouth side (vortex flow domain), and the other is the mainstream zone where the outflow is close to the hub side (mainstream domain) [8]. The static pressure in vortex flow domain is clearly larger than that in main flow domain from the experiment in [8].

In Lee's model [4], only the dynamic pressure is involved in the calculation of radiate energy, and the effect of static pressure is neglected. In order to considerate the influence of static pressure, a pseudo-velocity V^* is proposed in this study by dimensional analytical method,

$$P_{st} = \frac{\rho}{2} V^* \times V^* \tag{13}$$

$$V^* = \left(\frac{2P_{st}}{\rho} \right)^{1/2} \tag{14}$$

which is used to correct the main flow velocity.

It is assumed that the influence of static pressure on the overall sound pressure level only exists in vortex flow domain. Then the critical value of the static pressure used to calculate the pseudo-velocity V^* is the minimum value in vortex flow domain. On the other hand, it is assumed that the influence of static pressure to the overall sound pressure level is negligible in mainstream domain. Thus, the critical value about static pressure is also the maximum value of static pressure in mainstream domain,

$$V^{**} = \left(\frac{2\max(P_{st} - P_r\ ,\ 0)}{\rho} \right)^{1/2} \tag{15}$$

where P_r is the critical pressure, which is taken as the minimum value of static pressure in vortex flow domain.

As such, the corrected velocity is defined by,

$$V_a^* = V_a + V^{**} \tag{16}$$

Then the total radiated energy can be expressed as,

$$e = \frac{\rho}{24\pi a_o^3} \int_{span} \frac{(KV_a^* V_i)^2}{cb_x b_z} \times \left\{ \left[\sum_{n=1}^{\infty} (-1)^n (\alpha_n - 1) \right]^2 + \left[\sum_{n=1}^{\infty} (-1)^n \frac{\omega c}{2V_a^*} \left(\alpha_n - \frac{1}{\alpha_n + 1} \right) \right]^2 \right\} dz \tag{17}$$

There is a relationship between the sound power and the sound pressure p [4],

$$e = \frac{8\pi l^2 p^2}{3\rho a_0} \tag{18}$$

where l is the distance from the test point to the noise source.

The Eq. (18) can be re-written as [6],

$$p^2 = \sum_{n=1}^{B} p_i^2 = \sum_{n=1}^{B} \frac{3\rho a_o e}{8\pi l_i^2} \tag{19}$$

where B is the number of blades.

The overall sound pressure level is defined as,

$$SPL = 20\lg\frac{p}{p_{ref}} = 10\lg\frac{p^2}{{p_{ref}}^2} \tag{20}$$

where p_{ref} is a reference pressure which is equal to 2×10^{-5} Pa.

Results and Discussions

Fukano et al. did experiment for an airfoil-shaped axial fan [10], and compared the predicted overall sound pressure with Lee's model and the experimental data. The result shows that the predicted overall sound pressure is lower than that from experiment [10], as shown in Fig. 4.

The reason for the discrepancy between the theory and the experiment may be due to the separation of boundary layer. The prediction result with the improved model which considering the effect of boundary layer separation on the suction surface is also plotted in Fig. 4. It is seen that the modified model agrees better than Lee's original model with the experiment. Thus, considering the effect of boundary layer separation, the sound pressure level can be predicted more accurately.

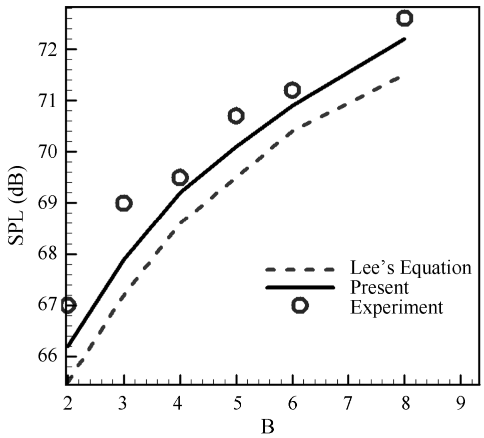

Fig. 4 Overall sound pressure of the axial fan versus number of blades; The experimental data is taken from [10]

Sasaki et al. did experiment for a multiblade centrifugal fan [8]. In their study, the flow field in the fan is simulated with commercial software Fluent. The simulation results of the efficiency and total pressure of the fan are compared with the experimental data as shown in Fig. 5 and Fig. 6, respectively. In Fig. 5, the ordinate is the efficiency η and the abscissa is the flow rate coefficient φ. In Fig. 6, the ordinate is the total pressure P_t and the abscissa is the flow rate coefficient φ. It can be seen that the simulated results agree well with the experimental data.

Figure 7 shows the distribution of relative velocity and absolute velocity versus the impeller width at the trailing edge of blade (where z=0 corresponds to the bellmouth side and z=1 corresponds to the hub side). As mentioned, the flow has been divided into two domains, main domain (hub side) and vortex domain (shroud side). It can be seen from Fig. 7 that the velocities in main flow zone is higher than those in vortex zone. This trend is in agreement with the experimental data [8].

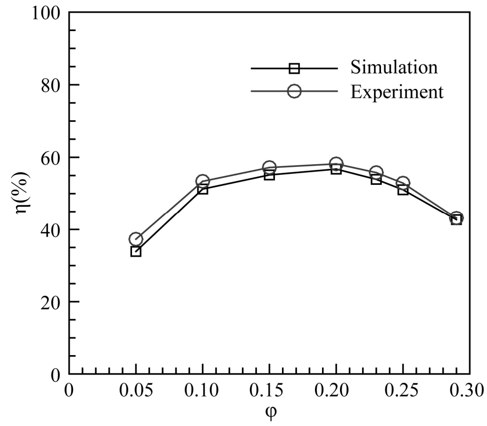

Fig. 5 Measured and simulated efficiency versusflow rate

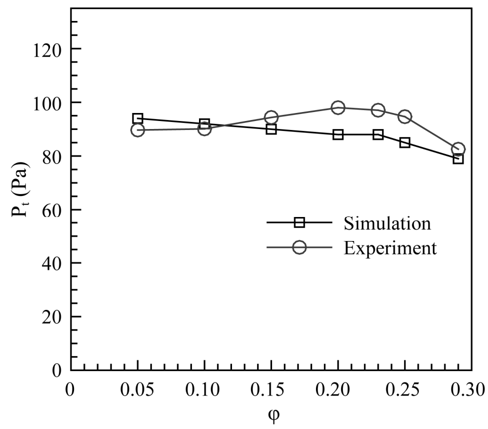

Fig. 6 Measured and simulated total pressure versus flow rate

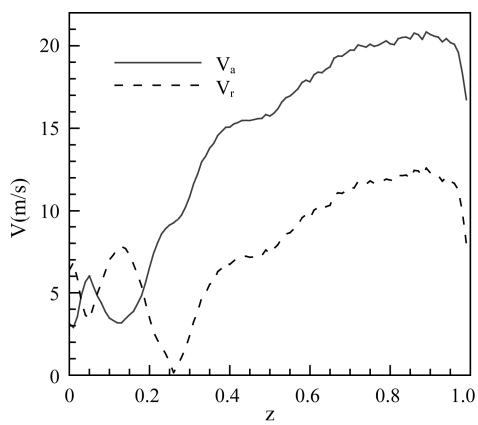

Fig. 7 Distribution of velocity along the blade height (V_a and V_r expresses the absolute and relative velocities, respectively)

If the vortex shedding noise generated from the wake of fan blades is the main noise source, the vortex shedding frequency is also the frequency of broadband noise. Thus, the relative velocity is used to calculate the frequency of broadband noise in Eq. (11). In the following calculation, the absolute velocity will be used to calculate the radiate energy in Eq. (17) because of the radiate energy is closely related to the absolute velocity.

Figure 8 is the distribution of static pressure at the impeller outlet along the trailing edge of blade (where z=0 corresponds to the bellmouth side and z=1 corresponds to the hub side). It can be seen that the static pressure in vortex flow domain is clearly higher than that in main flow domain. In the actual calculation of radiate energy, only the effect of static pressure in vortex zone is considered, while the effect of static pressure in main stream zone is not taken into account.

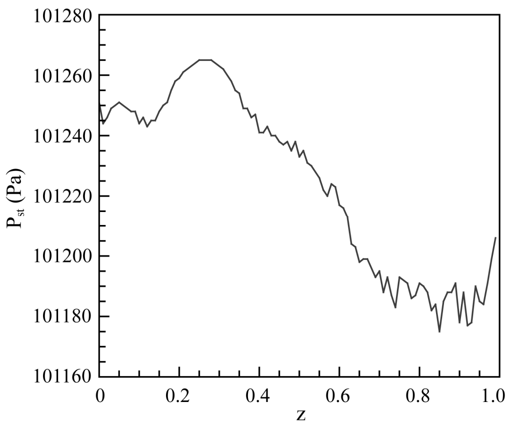

Fig. 8 Distribution of static pressure along the blade height

In Fig. 8, it can be seen that the static pressure is relatively high when 0<z<0.4. Taking into account the velocity along the trailing edge of blade, the region of 0<z<0.4 is regarded as the vortex flow, and the region of 0.4<z<1 is thought to be the main flow region. This partition is consistent with the result of the literature [8]. Thus, the static pressure at z=0.4 is taken as the critical pressure, P_r, in Eq. (15) for the detailed calculation of radiate energy.

In Fig. 9, the predicted broadband noise with the improved model is compared with experimental data in [8]. Result predicted with Lee's original model [4] is also included. The experiment on the fan was performed under the condition of 1400 r/min [8]. Thus, the discrete noise is generated in the blade path frequency about 2333Hz. In addition, because of the noise in high frequency is generated by harmonic mainly, this model mainly pays attention to the broadband noise which is generated from 100 to 2000Hz.

It can be seen from Fig. 9 that the frequency of broadband noise calculated by Lee's model is deviated from the broadband noise area.

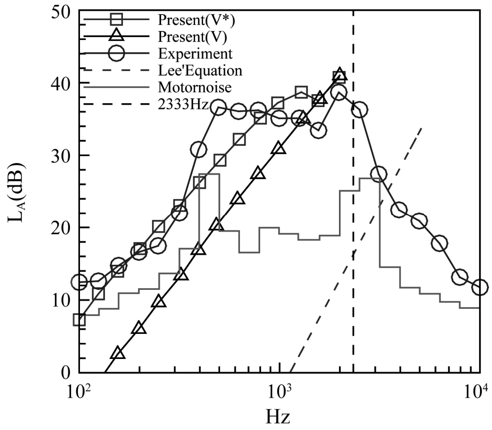

Fig. 9 Comparison of the predicted broadband noise with experimental data in [8]

With the improved model, the predicted A-weighted sound pressure level (L_A) is plotted in Fig. 9, where the frequency is calculated with the Strouhal number by Eq. (11). In the present calculation, St=0.2 is employed according to reference [8]. Without considering effect of static pressure, the predicted result is expressed as "present V". With considering effect of static pressure, the predicted result is expressed as "present V*" in Fig. 9.

It can be seen from Fig. 9 that both calculation results in this study agree well with the experimental data in range of 100Hz~2000HZ. With considering effect of static pressure, the predicted result of A-weighted sound pressure level (L_A) favorably accords with the experiment.

Conclusions

In the prediction of noise of fans, Lee's classic model is widely used by several researchers. However, this model compares poorly with experiments in some cases. In the present study, improvement on this model is carried out by considering effect of some factors.

Firstly, the boundary layer theory is used to analyze and calculate the boundary layer development on both the pressure and suction sides of blades. Considering the effect of boundary layer separation on the location of noise source, a simple improved model is constructed. The predicted overall sound pressure level compares favorably with the experimental data of an axial fan.

Secondly, in the calculation of A-weighted sound pressure level (L_A), considering the effect of static pressure on radiate energy, an improved model is proposed. The predicted broadband noise with the modified model compares favorably with the experimental data of a multiblade centrifugal fan.

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